AIR WAR COLLEGE

AIR UNIVERSITY

SPACE BASED INTELLIGENCE, SURVEILLANCE, AND RECONNAISSANCE CONTRIBUTION TO GLOBAL STRIKE IN 2035

by

Shaun R. Stuger, Lt Col, USAF

A Research Report Submitted to the Faculty

In Partial Fulfillment of Graduation Requirements

15 February 2012

DISCLAIMER

Biography

Lieutenant Colonel Shaun R. Stuger

Lieutenant Colonel Stuger is a space operations and acquisition officer currently enrolled as a student at the Air War College (AWC). He was commissioned through the Air Force ROTC in 1990 where he earned a Bachelor's degree in Computer Science. Since then, he has also earned a Master of Science degree in Technology Management from Pepperdine University, Malibu, CA. During his career Lt Col Stuger has served in a variety of space operations, acquisition, and staff assignments. Prior to AWC he served as the Space Operations Squadron Commander/Chief, Engineering and Production Division, Aerospace Data Facility East, Virginia commanding a 500+ member government and industry team responsible for the day-to-day and long-term engineering of ground systems for a multi-satellite, multi-billion intelligence constellation. Lt Col Stuger also deployed to Afghanistan where he served as the Deputy Chief, Acquisition Division, Office of Security Cooperation, Afghanistan (OSC-A). He functioned as an acquisition mentor to the Afghan Ministry of Defense, and advisor to the Minister for Acquisition Technology and Logistics on Afghan National Army procurement matters. He was recently selected to take command of the Space Command & Control and Surveillance Division, Peterson AFB, CO in the summer of 2012.

Abstract

This paper provides an argument for the U.S. Air Force to invest in a robust space-based Intelligence, Surveillance, and Reconnaissance (ISR) architecture to support Global Strike in 2035. The detailed investigation provides recommends on future technologies the Air Force can pursue, which will provide relevant space-based ISR capabilities in a congested, contested, and competitive space environment. As these technologies progress and enable continuous space-based ISR collection in the congested, contested, and competitive space environment of 2035 U.S. decision makers will be able to strike globally putting any adversary target at risk. Space-based ISR, along with airborne ISR and cyber, will be able to provide global, ever-present ISR. By 2035 this multi-sensor, multi-domain approach to ISR collection can enable U.S. leadership to consistently operate within an adversary's decision making and action cycle, thus helping enable Global Strike. A comprehensive review of the current space-based ISR environment is followed with a review of alternative short-term and complementary solutions. The short-term and complementary solutions offer a level of ISR capability to satisfy many user requirements, but are insufficient to satisfy unique user requirements. In order to satisfy those unique requirements investment in advanced space-based ISR capabilities is needed. Operationally Responsive Space (ORS) and small satellites are recommended as two means of enabling advanced space-based ISR capabilities to support Global Strike in 2035. By 2035 ORS can provide a rapid, flexible and adaptable method to reconstitute denied, degraded, or destroyed space-based ISR assets. Additionally, smaller, lighter satellites can be launched more easily on ORS systems, and be enabled by advances in nanotechnology and propulsion technology. These small satellites can be flown in formation and be more difficult for adversaries to target. The research indicates that an integrated space-based ISR, airborne ISR, and cyber architecture will grow to be a major enabler of Global Strike in 2035.

I. Introduction

"During the past 50 years, U.S. leadership in space activities has benefited the global economy, enhanced our national security, strengthened international relationships, advanced scientific discovery, and improved our way of life." Robert M. Gates, Secretary of Defense and James R. Clapper, Director of National Intelligence, 2011[1].

In the next fifty years space systems will grow to be an even more integral part of the above activities. Space-based Intelligence Surveillance and Reconnaissance (ISR) systems will be able to provide vital contributions to United States national security, particularly in relation to Global Strike in 2035. As a result, it will be necessary to examine the environment, threats, and technologies that encompass space-based ISR and propose a way ahead for it to support Global Strike in 2035. Secretary Gates' and Director Clapper's statement, as lead-in to the National Security Space Strategy, sets the tone for the critical role space capabilities have played and will continue to play for the U.S. In particular, space-based ISR systems will provide decision makers situational awareness on everything from adversary actions and target location to natural disasters. These systems will provide data across multiple sensor types enabling continuous Find, Fix, Target, Track, Engage, and Assess (F2T2EA).

Space-based ISR will be one of several capabilities that will be integrated to provide ubiquitous ISR. Along with Airborne ISR and Cyber, space-based ISR will be a major element of a multi-sensor, multi-domain, real-time intelligence capability transforming information into actionable knowledge, thereby allowing machines to execute human intent at machine speeds.[2] As such, U.S. decision makers will be able to operate systematically within an adversary's Observe, Orient, Decide, Act (OODA) loop. In the event that any of the U.S. space-based ISR architecture is degraded, denied, or destroyed, there will be several mitigating options in the form of complementary space-based ISR and launch capabilities[3]. The nation's ISR satellites are procured and operated in large part by Air Force Space Command's (AFSPC) Space and Missile

Systems Center (SMC), and the National Reconnaissance Office (NRO). The main customer base for AFSPC is the Department of Defense, while the main customer base for the NRO is the intelligence community (IC), comprised of a myriad of intelligence agencies. As space-based ISR grows to be a major enabler for Global Strike, U.S. space-based assets could be subject to degradation, denial, or destruction. Continuous F2T2EA along with execution at machine speeds will help negate these threats. The stream of intelligence gathered using space-based ISR will allow the Find, Fix, Track, Target, Engage, and Assess serial cycle to be more dynamic and much more rapid. The speed at which our systems will be able to operate will be faster than the time it takes our adversary to Observe, Orient, Decide, and Act as depicted in Figure 1 below[4].

Figure 1: Dynamic FFT2EA Cycle Allows U.S. to Operate Within Adversary OODA Loop

Technologies exist today that enable robustness and reconstitution. In August of 2011 Gen Bruce Carlson (USAF, Ret), Director of the NRO indicated they will continue to use small satellites to develop and demonstrate innovative technologies. These technologies will solve users' most challenging problems, greatly reduce design to launch timeline, fly in formation in order to produce large synthetic apertures for higher resolution, and rapidly change on-orbit configurations in response to evolving mission sensing requirements.[5] The NRO, the Air Force, and private corporations are exploring more ways to leverage technologies that will enable these capabilities. In the years leading up to 2035 those technologies will continue to advance providing off-ramps to newer, arguably better capabilities. Space-based ISR will be a major contributor to Global Strike in 2035, but the investment needs to happen today. This paper will explore the environment, threats, and technologies that encompass space-based ISR and propose a way ahead for it to support Global Strike in 2035.

Section II will first examine the current space-based ISR environment by reviewing the mitigating actions that can be taken in a congested, contested, and competitive space environment. The actions include using high altitude air platforms and airships as a short-term solution, and small satellites with an Operationally Responsive Space (ORS) launch capability as a more robust, complementary, long term solution. Section III will review the continuum of threats examining reversible and irreversible threats, along with a worst case scenario. Section IV provides greater detail of the high altitude air platform, airship, and commercial space-based ISR short-term mitigating actions, while section V provides a detailed review of ORS and small satellite technologies. The paper concludes with a recommendation for investment in some of these future technologies to ensure a robust, redundant space-based ISR capability that will be able to support Global Strike in 2035. The current space-based ISR environment will be explored in the next section.

Examining the current space-based ISR environment is the first crucial step in determining which actions will be appropriate in the congested, contested, and competitive space environment. As more entities begin to leverage space as a strategic and tactical frontier the U.S. will need to respond equally. The high ground of space cannot be left vulnerable.

II. Current Space-Based ISR Environment

During testimony before the Senate Armed Services Committee for Strategic Forces Ambassador Gregory Schulte, Deputy Assistance Secretary of Defense for Space Policy noted that “the current and future strategic environment is driven by three trends—congested, contested, and competitive.”[6] Regarding the trend of congestion, the radio frequency spectrum for space applications continues to become more congested, and as more nations’ get into the space business their satellites and space debris, illustrated in Figure 2, are causing more physical congestion. The trend of space being a contested area will continue to grow as more countries look to get their systems into space. Space will be a frontier in which the U.S. will continue to be challenged as countries such as China and Russia strive to gain primacy. The third trend of competitiveness has also increased with companies like Geoeye and DigitalGlobe, and countries such as the United Kingdom, Canada and Germany[7].

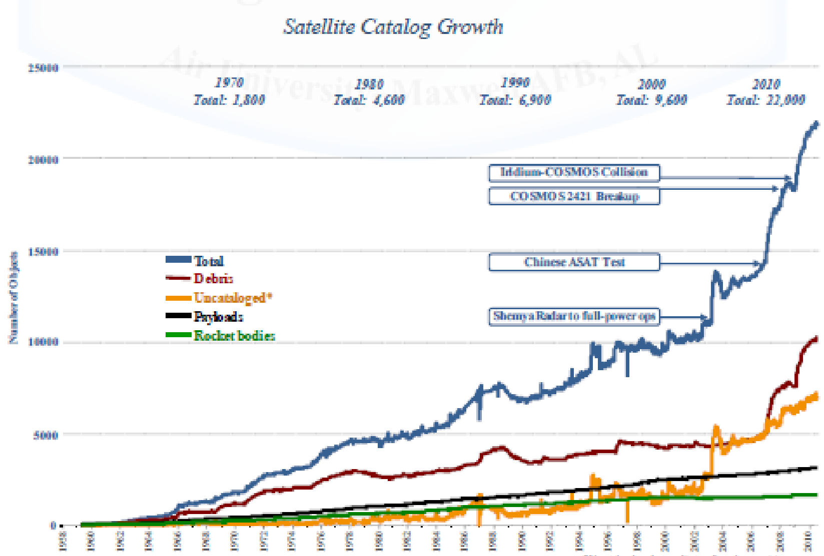


Figure 2: Source – National Security Space Strategy via the Joint Space Operations Center

Mitigating Actions

As mentioned above myriad organizations will have access to space and the space environment will continue to be congested, contested, and competitive. Resultantly, the U.S. could use high altitude air platforms, airships, and cyber to complement its space systems in case of denial, degradation, or destruction. However, the effects of adversary actions could initially be mitigated as the U.S. develops more robust and redundant space systems. These two sets of actions need to be considered as an overarching approach to ensure continuous, robust space-based ISR to support Global Strike in 2035.

The first set of actions are a stop gap since high altitude air platforms, airships, and cyber do not provide the broad area, continuous coverage of space-based systems. They can however provide some capability in the event U.S. space-based ISR cannot optimally function.[8] The second set of actions provides a measure of prevention up front. By developing a robust, redundant space-based ISR architecture up front, the ability of an adversary to deny, degrade, or destroy systems that comprise this architecture diminishes.

Current Space-Based ISR Architecture

The current U.S. space-based ISR architecture is comprised of satellites in low earth orbit (LEO), 500 to 2,000 kilometer altitude; medium earth orbit (MEO), 8000 to 20,000 kilometer altitude; highly elliptical orbit (HEO) with a perigee (closest point to the earth) of 500 kilometers and an apogee (furthest point from the earth) of 50,000 kilometers; and geostationary orbit (GEO), with an altitude of approximately 36,000 kilometers (See Figure 3).

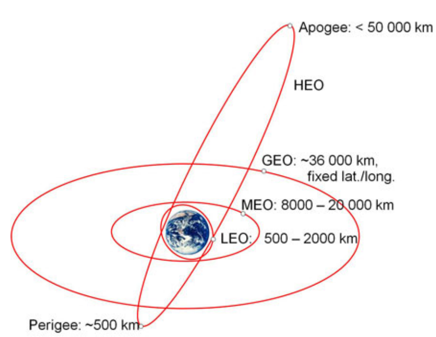


Figure 3: Orbit Types[9]

Each orbit type has its advantages and disadvantages for space-based ISR applications. Due to its proximity to the earth, a system in LEO has better resolution; a higher revisit rate over points of interest on the earth; but requires more satellites for global or regional coverage; and is more susceptible to threats. A system in MEO can provide global or regional coverage with fewer satellites; has more continuous coverage of an area due to its orbit; provides more reaction time in case of launched threats; but requires a larger sensor to obtain a similar resolution as LEO systems; and more power to launch and position into a final MEO orbit. A system launched into a HEO orbit has the advantage of hours of continuous coverage over an area of interest. A GEO system would be more difficult for an adversary to threaten because of its distance from the earth; however, the resolution of a system in GEO is less than the previous three systems; and requires more power to launch into its orbit.

A MEO orbit seems to provide the best attributes for an ISR satellite constellation to contribute to Global Strike in 2035. First, a MEO orbit could provide U.S. space-based ISR systems the distance to react to launched threats, requires fewer satellites for global or regional coverage, and is not as costly as putting similar systems into GEO. Secondly, developing small satellites and nanotechnology for MEO based systems will provide a more dispersed, tougher to reach target set. Finally, some investment needs to transition from the larger, “Cadillac” type satellites to these areas in order to achieve affordable robustness and complementary MEO based ISR in support of Global Strike 2035.

Although U.S. space-based ISR satellites are extremely capable, there is a tradeoff in cost. By integrating exquisite capabilities, building in system redundancy, and manufacturing more robust components, these bigger, more capable satellites have increased proportionately in cost. Launch costs for bigger, heavier systems are also skyrocketing. There is an argument to be made that the space-based ISR capability in current U.S. systems should be allowed to grow, however there is also an argument to be made that a balance needs to be struck between capability and budget. The lifecycle costs of exquisite systems will likely become more difficult to afford as budgets continue to tighten. Unlike air systems, the majority of lifecycle costs for space systems are paid up front, with a smaller portion of those lifecycle costs paid to operate the satellite and maintain the ground system.[10] An alternative to fewer more expensive, exquisite systems is cheaper, mass produced smaller satellites. This concept will be explored in additional detail later in this paper.

In relationship with the concerns addressed above, a review of the DoD's and the National Reconnaissance Office's (NRO's) space-based ISR roadmaps yields mixed results. The systems being procured in the near term are focused on supporting today's conflicts and disasters. Today's systems possess unique technologies such as electro-optical sensors, radar sensors, infrared sensors, multi-spectral sensors, or hyper-spectral sensors; they also enable unique capabilities such as persistence, precision, and 24 x 7 battle damage assessment. Without space-based ISR, DoD and intelligence community users would not be able to accurately assess the tactical and strategic landscapes. Although the environment is changing to include more airborne and cyber systems, space-based ISR still remains a vital part of the overall ISR architecture[11]. As cyber and airborne use continue to grow, it will be essential that DOD and the NRO work to ensure space-based ISR matures as the current environment continues to evolve.

Migrating from the Current Environment

In order to support Global Strike in 2035, space-based ISR systems will need to be flexible, adaptable, and cheaper than they are today. As mentioned, the competition from commercial satellites as well as other countries continues to grow. Today's space systems contribute to global military operations by providing ISR support to the combatant commanders (COCOMs) and the Intelligence Community (IC). Current systems are a limited resource, however future space-based ISR systems will be able to provide 24x7 support, and be tasked by both the COCOMs and IC. Space-based ISR systems will have developed substantially by 2035 and will be a major enabler of providing intelligence at one's fingertips. By 2035 Space-based ISR will contribute greatly to transparency by providing continuous imagery, signals, and electronic intelligence for any area on earth. The ability for the U.S. to collect and exploit this type and amount of information will almost certainly provide an impetus for others to try and negate the ability for the U.S. to perform these actions.

By 2035 technology to deny, degrade, or destroy U.S. space-based ISR systems will also likely advance. Previously, the U.S. only needed to be concerned about other nations posing a threat to space related assets. Over the previous two decades technology has progressed to the point in which smaller and smaller groups have been empowered. By 2035 individuals could possess the same amount of destructive power some small nations possess today as depicted in Figure 4 below. The continuum of threats is explored in the next section.

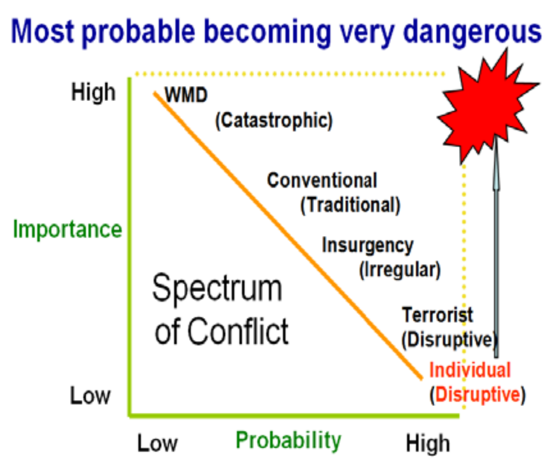


Figure 4: Disruptive Technology Migrating to More Individuals. Credit CSAT.

III. Threats

To support Global Strike in 2035, military space systems will need to provide global intelligence, surveillance, reconnaissance, and communications. Potential adversaries recognize our critical dependence on space assets and are developing means for disrupting our access, or even for incapacitating or destroying those assets.[12] As it stands today, there are more governments, companies, and organizations gaining access to space (See Figure 5). The threats potential adversaries pose span a continuum from ground based cyber-attacks on U.S. command and control systems to anti-satellite weapons and nuclear detonation. In the future the threat will grow to include nations, groups and individuals. Even these "Bubba Einsteins," an individual that has access to powerful technology and is willing to use it, could possess enough disruptive technology to pose a serious risk to U.S. space systems. These threats to our satellites fall into two categories, reversible and irreversible. Systems can be recovered from a reversible threat while irreversible threats deteriorate systems to the point where they cannot be recovered.

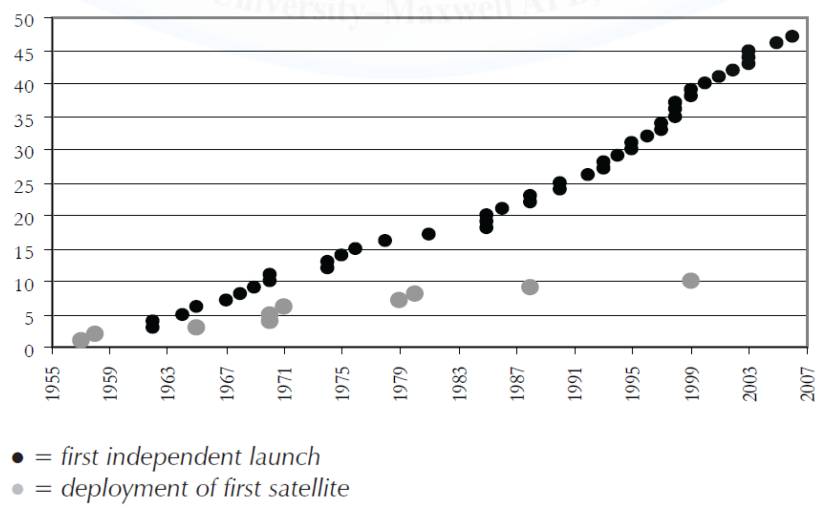


Figure 5: Growth in National Actors Accessing Space[13]

Reversible Threats

In order for U.S. space-based ISR systems to be robust and complementary the threat environment must first be understood. Reversible threats to U.S. space-based assets include cyber-attack to associated command, control communications, and information (C3I) systems; jamming of satellite communications uplink and/or downlink; and use of low power laser to dazzle satellite systems. Each of these threats has been proven and research into the latter of these threats is receiving more attention. Laser jamming affects the satellite directly, not just the C3I infrastructure[14]. An adversary can be more certain of the damage they are able to deliver using a laser system. Si-wen Wang, Li-hong Guo, and Ru-hai Guo of Changchun Institute of Optics, China have analyzed and confirmed that laser can disturb charge coupled detectors (CCD)[15]. CCDs are used in the digital imaging industry and are being used more and more on imaging satellites.

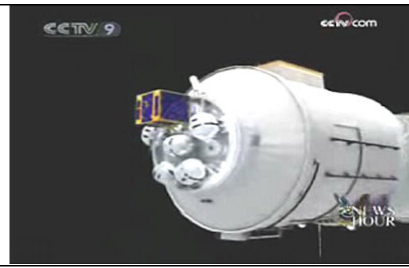
The degradation of a satellite sensor can be produced based on a satellite's orbit, the laser power, the distance of laser transmission, and atmospheric attenuation. The model they have developed uses these factors to identify the threshold for degradation of space-based surveillance and reconnaissance sensors[16]. Since a laser can be used for disturbance, pushing the power above a certain threshold will almost guarantee destruction of sensors or portions thereof. By understanding the nature of these threats U.S. space-based ISR systems can be built to lessen the impact of these threats.

Irreversible Threats

Irreversible threats to U.S. space-based assets include high-power laser that can cause permanent damage to satellites; anti-satellite (ASAT) weapons that can be selective, but will still cause space debris; and destruction of other space system assets including ground stations. China is already developing a comprehensive ASAT program that includes not only lasers, but direct-ascent ASAT missiles[17], as was successfully demonstrated in 2007, and co-orbital systems to deny others access to space[18]. The Chinese military used a ground-based missile to hit and destroy one of its aging satellites orbiting more than 500 miles in space [in January 2007]—a high-stakes test demonstrating China's ability to target regions of space that are home to U.S. spy satellites and space-based missile defense systems[19]. The ASAT test conducted by China in 2007 proved successful, but also detrimental, in that debris remained in the destroyed satellite's orbit[20].Following this show of force by the Chinese, the U.S. launched its own direct ascent ASAT in March 2008 to destroy a failed satellite[21]..

Another potentially irreversible threat is an orbital system launched into the same orbit as its potential target satellite. This co-orbital ASAT can negate another satellite without disclosing the actual cause. China's microsat experiment has shown that they possess the requisite technology to accomplish that goal. According to official reports by the Chinese media and interviews with Chinese officials, China's BX-1 satellite was to provide images of the Shenzhou-7 (SH-7) capsule and demonstrate the ability to inspect the orbital module and conduct some limited proximity operations. It also carried out a data relay experiment. However, some observers have concluded that the BX-1 was actually a test of some of the capabilities required for a co-orbital anti-satellite (ASAT) attack[22]. According to Craig Covault, in 2009 the U.S. performed the first deep space inspection of a crippled Defense Support Program (DSP) satellite[23]. By performing this deep space inspection, the U.S. has also proven it's capable of developing a co-orbital ASAT (See Figure 6).

The USS Lake Erie launches a missile at a non-functioning U.S. satellite. Credit USA Today.



China's BX-1 satellite attached to the Shenzhou 7 orbital module. Credit CCTV.

Lasers fire from Starfire Optical Range at Kirtland Air Force Base, N.M. Credit ZDNet.com.

Figure 6: Anti-Satellite Technologies

Satellite command and control, antenna facilities, launch facilities, or data storage facilities can also be targets for attack. An attack on the physical infrastructure can cause long-term degradation of capabilities as well as have a negative psychological impact on the ground station population. Physical attacks and/or sabotage can be used against the critical ground facilities associated with US space systems in an effort to disrupt, deny, degrade, or destroy the utility of the space system[24]. A risk mitigator could be more distributed operations. There has been the tendency of putting all of our space operations facility eggs in one basket.

Worst Case Scenario

The final irreversible threat, and one which can be a worst case scenario, is a nuclear detonation (NuDet) in the atmosphere or space. Dennis Papadopoulos from the University of Maryland Physics department stated "LEO constellations present tempting targets to future nuclear-missile-armed rogues… [and] LEO constellations may be destroyed as a by-product of nuclear detonations…"[25] He also indicated there would be impact to civilian and military space-based capabilities causing social, economic, and political damage[26]. The general consensus of the space community is that as countries continue to grow in satellite usage and become more dependent on space they will be less likely to use a NuDet as a means of denial, degradation, or destruction. Although the number of actors in space capabilities is increasing, the likelihood of a NuDet is still very small.

By understanding the nature of threats against U.S. space-based ISR systems future systems can be optimally developed and launched to minimize the impact of these threats. The resulting space-based ISR architecture will thus be able to provide continued support Global Strike in 2035. Although alternative systems such as airborne ISR, cyber, high-altitude air platforms, airships, and commercial space-based systems can provide ISR capability they are not immune to denial, degradation, or destruction. If fact, U.S. cyber systems are continuously being exploited, while airborne systems are easier to detect and negate, based on their closer proximity to the surface of the earth, than space-based systems. This paper only reviews high altitude air platforms, airships, and commercial space-based ISR as short-term, alternative solutions that can provide some capability until space-based systems can be reconstituted. These short-term, alternative solutions, which will provide support to Global Strike 2035, are discussed in the next section.

IV. Short-Term ISR Capability

To support Global Strike in 2035 high altitude airborne sensors can provide some capability in case of denial, degradation, or destruction of space-based ISR assets. Although, they would not have as extensive a geographic coverage and persistence as satellites, these systems could supplement space-based intelligence gathering capabilities. They could also provide relatively rapid reconstitution and a short-term solution for space-based ISR loss[27].

High Altitude Air Platforms

High altitude aircraft as shown in Figure 7 can provide short-term ISR capability if space-based systems are denied, degraded, or destroyed. Systems such as the U-2 have shown great utility for the CIA and Air Force since the 1950s. Demonstration systems such as Boeing's unmanned demonstration Phantom Eye aircraft could also fill the gap. The hydrogen-powered Phantom Eye unmanned airborne system can stay aloft at 65,000 feet for up to four days[28].

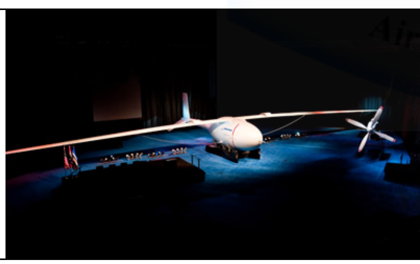
		
Boeing's Phantom Eye High Altitude Long Endurance Aircraft. Credit: The Boeing Company.	Lockheed Martin's U-2 Credit: Lockheed Martin.	Northrop Grumman's RQ-4 Global Hawk. Credit: Northrop Grumman.

Figure 7: High Altitude Air Platforms

In 2009 Lieutenant General Dave Deptula, Deputy Chief of Staff, Air Force Intelligence, Surveillance and Reconnaissance said "in the 21st Century ISR is operations – it's not simply support…by virtue of ISR presence alone we can affect enemy behavior."[29] In addition to high altitude air platforms the Air Force is continuing to invest in airship technology. Airships provide a cheap alternative in providing persistent, albeit limited, ISR capability.

Unmanned Airships

Unmanned airships, as shown in Figure 8, also have the potential to fill in for space systems to perform ISR tasks. However, they sacrifice speed in exchange for endurance and would have to be prepositioned in the likelihood that something is eminent and the capability could be used. The response to an attack though would likely be slow and therefore put the airship in jeopardy. Additionally, their coverage compared to satellites is more limited since they are closer to the earth's surface[30]. Both military and commercial organizations are developing airships and optimizing associated sensors.

		
Lockheed Martin's HALE-D. Credit: Lockheed Martin.	SAIC's Skybus 80K Lighter Than Air (LTA) UAS. Credit: SAIC.	E-Green Technologies Model 580 Bullet Airship. Credit: E-Green Technologies

Figure 8: High Altitude Airships

Commercial Systems

Finally, the use of commercial satellite systems, as shown in Figure 9, can also provide some space-based ISR capability. Space-based ISR from the commercial sector continues to grow as both government and commercial industries look to reduce costs and ensure their customers receive relevant and timely intelligence. Companies such as Geoeye, DigitalGlobe, and Surrey Satellite Technology Limited (SSTL), U.K. continue to garner contracts in the 100s of millions, and accolades from government and commercial companies.

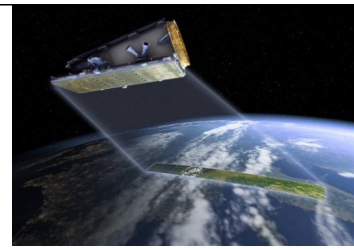
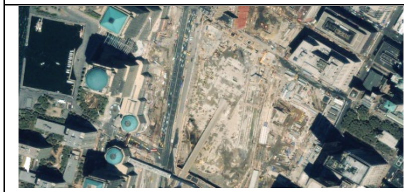
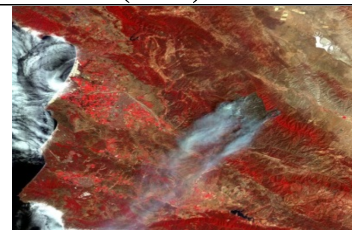
 Geoeye 1 Satellite	 DigitalGlobe Quickbird Satellite	 Surrey Satellite Technology Limited (SSTL) NovaSAR-S
 Manhattan, New York (World Trade Center - Aftermath Cleanup Effort), June 8, 2002. Credit – Geoeye.	 Damage at missile-related facility near Bidgeneh, Iran, caused by a November 12, 2011 explosion. Credit – DigitalGlobe.	 California Fires. Credit – SSTL.

Figure 9: Commercial Space-based ISR Satellites

The variety of sensor types and the quality of the imagery may not be as good as that provided by Air Force Space Command's (AFSPC) or the National Reconnaissance Office's (NRO) systems, but as a short-term gap filler commercial systems can provide some ISR capability.

National decision makers rely on AFSPC and NRO systems for imagery, signals, and electronic intelligence; and intelligence based products they cannot get from other systems. As reliance on space-based ISR continues to grow U.S. space systems, from ground to satellites, will be vulnerable to denial, degradation, or destruction. This section explored some short-term alternatives that could provide ISR capability. The next section focuses on future technologies that can be developed to preempt threats against U.S. space-based ISR systems.

V. Future Technologies

Investment in future technologies is critical. By 2035 the U.S. will certainly face a continuum of threats from nations, to groups, to individuals. It then remains imperative that the U.S. invest in technologies that ensure its preeminence in space and provide the ability to act, or react decisively. Operationally Responsive Space (ORS) and small satellite technology are two key areas which can mitigate the effects of adversary denial, degradation, or destruction of U.S. space-based ISR systems. Finally, nanotechnology and propulsion advances, as enablers for small satellite technology are explored.

Operationally Responsive Space

In 2007 the Department of Defense committed to establishing Operationally Responsive Space (ORS) as a means to provide rapidly augment or reconstitute space-based capabilities[31]. This on-demand capability can be a key part of reconstituting space-based ISR capabilities to support Global Strike in 2035. The ORS office has launched four minisatellites to date. Table 2 below highlights the launches and capabilities. The latest ORS satellite, ORS-1, was recently transitioned to Air Force Space Command's 14th Air Force, who will operate and task the satellite in direct support of U.S. Central Command (USCENTCOM). In support of Global Strike 2035 this operational concept will allow decision makers to exercise ORS as part of a comprehensive approach to rapidly augment or reconstitute space-based ISR assets.

ORS System	Launch Date	Launch Vehicle	Main Payload(s)	Orbit	Mass (kg)
TacSat-2	16 Dec 2006	Minotaur I	Electro Optical, Signals Intelligence	LEO	370
TacSat-3	19 May 2009	Minotaur I	Electro Optical, Hyperspectral	LEO	400
ORS-1	29 Jun 2011	Minotaur I	Electro Optical, Infrared	LEO	450
TacSat-4	27 Sep 2011	Minotaur IV	Communications (10 Ultra High Frequency Channels)	HEO	460

Table 1: ORS Launches[32]

Based on the ability to launch smaller satellites quickly, ORS can be a great benefit in support of Global Strike 2035, but up front commitment will need to be continued. America's forthcoming "Prompt Global Strike" non-nuclear hypersonic missiles will be able to hit almost any spot on earth in less than an hour—provided excellent satellite data is available[33]. All eyes will be on 14th Air Force and USCENTCOM as they continue to work together using ORS-1 and develop procedures and a Concept of Operations (CONOPS) that can set the foundation for future ORS systems.

A potential complimentary capability to the current ORS system is true launch on demand. The benefit of such a system is that the U.S. can warehouse cheaper satellites and boosters, but the downside will likely have to be an expectation and acceptance of technology decay. The U.S. would have to be willing to live on trailing edge, not the leading or cutting edge of technology. However, capability can be provided in a substantially shorter amount of time since the requisite systems would be available on demand. Another great benefit is quick reaction, but quick reaction small boosters need smaller payloads. To date, the trend in ORS launches has been small payloads[34]. Success in this area will almost certainly guarantee continued investment in small satellite technology.

Small Satellites

Small ISR satellites will be a crucial part of supporting Global Strike 2035 by providing complementary capability as well as making it more difficult for an adversary to deny, degrade, or destroy U.S. space-based ISR. Smaller satellites are proving to be faster, cheaper, and are expected to be more advantageous in the future as government budgets shrink. Investment, research, and development in smaller satellites should be a major component of the U.S. space roadmap. Governments and companies continue to seek savings on manufacturing costs of satellite systems. Analysis on spacecraft manufacturing, similar to most instances in which items are mass produced, has shown a decrease in the Average Procurement Unit Cost (APUC) for satellites as more are produced in the same manufacturing line. Smaller satellites also have a general advantage of having a lower overall cost per satellite than exquisite, larger satellites. This reality, along with mass production, economy of scale, and manufacturing learning curves (see Figure 11), could potentially drive substantial cost savings in satellite procurement for systems operating in the 2035 timeframe.

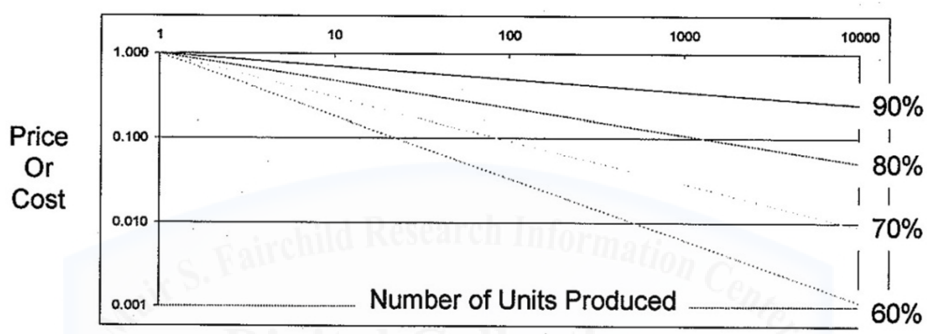


Figure 10: Spacecraft Manufacturing Learning Curve[35]

Many organizations have been investing in and exploring the benefits of microsats for several years; the dedication is beginning to pay off. Component miniaturization, increased processing speed, improved satellite materials, improved sensors, and a reduction in overall system costs have all contributed to this stimulation of satellite technologies. Small companies such as Comtech AeroAstro, Inc., Ashburn, VA, as well as industry leaders such as Northrup Grumman, Redondo Beach, CA are leveraging these advances. In February of 2011 the NRO launched a pathfinder in the minisatellite category. The total time to acquire and launch the minisat was less than 2 years at a cost of approximately $20M. Classes of satellites can be seen in Table 4 below.

Category	Mass (kg)
Large satellite	> 1,000
Medium-sized satellite	500-1,000

Minisatellite	100-500
Microsatellite	10-100
Nanosatellite	1-10
Picosatellite	0.1-1
Femtosatellite	< 0.1

Table 2: Satellite Mass Categories[36]

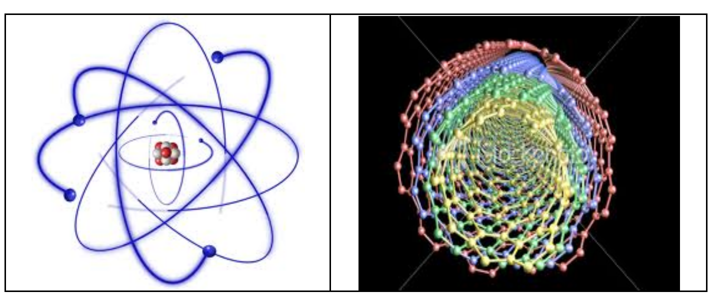
In addition, many countries are beginning to realize the benefits of small satellites. For example, the Royal Dutch Defence Academy is working on a technology and operations concept for a constellation of small satellites which can operate more safely than a big satellite. They have assessed that distributed satellites would be much more difficult to negate than a single larger satellite[37]. The use of smaller satellites and the resulting lower launch costs will enable more satellites to be launched more cheaply, and will provide quicker reaction for augmenting or reconstituting space-based ISR systems. Launching a payload to low-earth orbit can cost $20,000 or more per kilogram. But small satellites, including shoebox-sized “cubesats,” are often used in place of the ballast carried by rockets to improve their weight distribution. This “almost free ride to orbit” is fuelling entrepreneurship and innovation, says Aaron Rogers, a designer of intelligence and military satellites at John Hopkins University’s Applied Physics Lab in Maryland[38].

The U.S. government has to begin looking at alternatives for today’s larger space-based ISR systems. Mini, micro, nano, etc. satellites could someday compliment and/or replace these larger satellites. Considering the fact that a Tomahawk cruise missile costs $600,000 and is completely expended in a single mission, it seems reasonable to spend $1.1 million or less on microsatellites (not including some of the one-time infrastructure costs) that are launched for a single mission but provide a few months of useful life[39]. Smaller systems enable flexibility lacking in the larger, exquisite-class space-based ISR systems and could be further enabled by technology breakthroughs in nanotechnology and satellite propulsion.

Nanotechnology as an Enabler for Small Satellites

Global Strike in 2035 will rely heavily on space-based ISR. By 2035 launch will be cost prohibitive for the bigger, exquisite-class satellites. It thus becomes imperative for satellites to become smaller and lighter, while maintaining core capabilities. Nanotechnology will help the U.S. move in that direction. Innovations in materials, computing, and sensing have the potential to be major game changers in the space industry. The harsh environment of space poses a big challenge for satellites to operate within. Geomagnetic storms and solar radiation affect satellites by causing charging external and internal to the satellite's surface, and single event upsets (SEUs) of a satellite's electronic components. Satellite manufacturers currently develop components to handle various levels of radiation, but advances in nanomaterials have the potential to produce much more radiation hardened, lighter, and stronger components that can withstand space's unforgiving nature.

In November 2011 University of California Los Angeles researchers were awarded a $4.5M contract to develop stronger carbon nanotube materials. Carbon nanotubes are several orders of magnitude stronger than steel and at least an order of magnitude lighter than steel. These tubes are comprised of carbon atoms, one of the most abundant elements on earth (see Figure 12). Potential space applications for carbon nanotubes include wiring due to conductive properties, electronic components, and satellite "skin" that might sense space anomalies before they impact the satellite.



Carbon Atom. Credit scientificlinux.org.	Multi-walled Carbon Nanotube.

Figure 11: Carbon Atom and Nanotube

Nanotechnology is also driving advances in computing by enabling components to be smaller, faster and lighter. Researchers around the country, including Massachusetts Institute of Technology and University of California Santa Barbara, are beginning to develop techniques for using nanotechnology in integrated circuits[40]. Additionally, companies such as IBM and Intel are helping fund these efforts. As briefed by Dr. John Geis at CSAT, Intel has developed their Ivy Bridge processor utilizing nanoscale lithography. Intel's Ivy Bridge chip circuitry is 22 nm and is the first 3-D chip. (see Figure 13). Continued advances in nanocomputing will help drive the state of the art in component miniaturization and computing power.

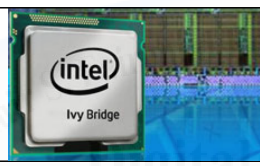
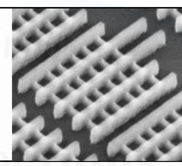
	
Intel chip. Credit CSAT.	Nanoscale 3-D lattice structure. Credit CSAT.

Figure 12: Nanoscale Lithography.

The size and processing speed of small satellites will need to be complemented with accompanying advances in sensor technology. Nanotechnology study in satellite sensors is also progressing. Researchers at Rensselaer Polytechnic Institute (RPI) were successful in developing a microlens using gold at the nanoscale level[41]. They were able to enhance the signal of an infrared detector by using nanoscopic gold to steer the light through the microlens surface (see Figure 14). Infrared sensors work by focusing the incoming energy onto the infrared detector, in this case the microlens. The accuracy of the signal is then determined by how much signal the microlens receives, divided by the noise. The microlens noise was very low thus making the overall accuracy of the signal in the RPI research extremely high. Professor Shawn-Yu Lin of RPI, noted "Infrared detection is a big priority right now, as more effective infrared satellite imaging technology holds the potential to benefit everything from homeland security to monitoring climate change and deforestation."[42]

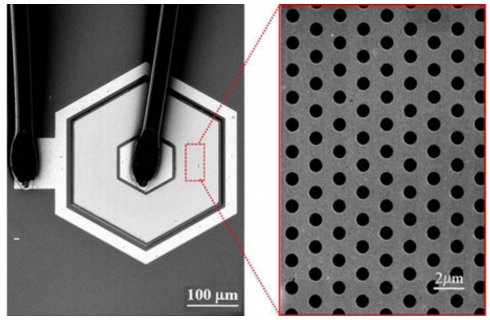


Figure 13: Microlens (left), surface magnification (right). Credit Gizmag.

Advances in Propulsion Enable Small Satellites

Another area that will be an enabler for space-based ISR, and thus Global Strike in 2035 is small satellite propulsion. Advances in propulsion can enable satellite formation flying using small satellites. Smaller satellites pose a more difficult target for adversaries. Instead of trying to target two or three larger exquisite-class satellites, they would have to target tens, possibly hundreds of small satellites. Simulations have confirmed the analytical assessment of researchers and show that simple techniques, which exploit the natural orbital motion to full extent, can meet the demanding requirements of long-term close formation flying[43]. Currently the only way for satellites to maneuver is with limited supplies of on-board fuel. In 2005 researchers at the Massachusetts Institute of Technology (MIT) studied electromagnetic formation flight (EMFF) as an alternative to fuel based propulsion. The study concluded that the use of powerful enough electromagnets could be used as a method to control relative positions of satellites flying in formation in a variety of space environments, including gravity wells and external magnetic forces[44]. Formation flying also enables distributed aperture systems, which can be advantageous by allowing several smaller ISR satellites, flying in formation, to simulate a larger aperture. As potential threats grow, maneuverability can become a vital aspect of survivability for satellite systems. Utilizing small satellites that are dispersed and have the ability to maneuver will, at the very least, provide transitory countermeasures to adversary actions.

As the U.S. looks to support Global Strike in 2035 investment in these technologies will prove to be a vital component of preempting, negating, and responding to adversary threats toward U.S. space-based ISR. The quick reaction launch capability Operationally Responsive Space provides along with small satellite technology, to include nanotechnology and propulsion, will provide U.S. decision makers with the flexibility they will require in an even more dynamic environment than exists today.

VII. Recommendations

The space environment over the next three decades will grow to be more congested, contested, and competitive[45]. The U.S. government can expect the development of adversary systems which will be able to deny, degrade or destroy U.S. space-based systems, including space-based ISR systems[46]. In order for space-based ISR to support Global Strike in 2035 investment in enabling technologies need to begin within the next 1-5 years. For example the requirements for the F-22 fighter aircraft were initially identified in 1981 with the system's first flight occurring in 1997, 16 years later[47]. The system finally became operational in 2005, 24 years after requirement definition. Now, this isn't an average acquisition timeline, but on average, space systems take 10-15 years to become fully operational[48]. A delay in requirements definition, research, and development (R&D) of space-based ISR systems could impact how Global Strike of 2035 is supported. Responsible U.S. governmental agencies should include further R&D of ORS technologies, and small satellite technologies—in the form of nanotechnology, and propulsion technology.

First, investment in Operationally Responsive Space (ORS) needs to continue. "An operationally responsive space system could be an integral part of national defense by providing operational capabilities, flexibility, and responsiveness that does not exist today."[49] The Air Force, as early as 2007 established a funding line of $409M for fiscal years 2008 to 2013[50]. By allocating a sufficient amount of funding to ensure ORS remains a viable program into the 2035 timeframe warfighter needs can be satisfied[51] and space-based ISR can be responsive to Global Strike needs. This approach will provide the U.S. an ability to rapidly augment or reconstitute space-based ISR systems[52].

Second, investment in small satellite technology[53] such as nanotechnology for satellite components, sensors, and propulsion systems can be game changers for space-based ISR and its contribution to Global Strike in 2035. "As satellites become smaller and smarter, they will become increasingly capable of sophisticated operations in orbit."[54] Nanotechnology will be a key area of research to enable development of nano-engineered materials with programmable optical/mechanical properties; nano-electronics and circuits for low-power computing, miniature space sensors, and highly efficient propulsion systems; and other nano devices which will enable adaptable, self-healing systems. In total, all of these nano technologies will drive satellite miniaturization[55].

Reductions in spacecraft size will in turn enable a decrease in launch costs and provide the ability to launch a greater numbers of satellites in a shorter amount of time[56]. There are two general trends that enable a reduction in launch costs. The first is payload weight[57] and the second is greater demand[58]. As organizations launch a greater number of small satellites per launch vehicle or a greater demand dictates more frequent launches efficiencies can be gained.

As Global Strike in 2035 looks to leverage a greater amount of space-based ISR the above capabilities will play an extremely important role. In response to the future space environment and future adversary threats space-based ISR systems will be able to provide vital contributions to U.S. national security in support of Global Strike 2035.

VII. Conclusion

Most acknowledge that U.S. space systems and space capability contribute greatly to its national security. Space-based ISR will continue to be a vital part of the United States' Global Strike Capability in 2035. In response to adversary action that could deny, degrade, or destroy our systems the U.S. space-based ISR architecture needs to be robust and quickly recoverable in response to denial, degradation, or destruction.

Options to restore or reconstitute denied, degraded, or destroyed space-based ISR assets include, but are not limited to commercial systems, airborne ISR, airships, and cyber. Although, they would not have as extensive a geographic coverage as dedicated satellites, these systems could supplement space-based intelligence gathering capabilities as they do today[59]. They could also provide relatively rapid reconstitution and a short term solution for space-based ISR loss. These alternatives also require investment from the U.S. government and will likely vie for some of the same funding required for a robust space-based ISR architecture.

The costs for the exquisite-class satellite systems are being pressured from multiple sides[60]. Congress, competing capabilities, and adversary systems pose continued risks to U.S. space-based ISR. The issues of unique manufacturing processes and equipment, all tend to drive costs higher. The goal therefore should be to migrate to a method of mass production of much smaller satellites, which can be launched on smaller boosters thereby lowering costs and making the future space-based ISR systems more competitive. Continued research in nanotechnology and will help develop materials, computing, and sensing capabilities. These technologies along with advances in propulsion science have the potential of enabling satellite formation flying, and distributed aperture systems.

A great benefit is that there's safety in numbers. Given a greater number of satellites for a potential adversary to attack, their investment will likely have to be substantial. It would be difficult for the adversary to discern which satellites to take out, or destroy them all at once. There could also be a positive cost benefit for the U.S. if it bought confusion to an adversary. It would be difficult for them to discern which systems they actually disrupted, degraded, or destroyed. This might provide sufficient time to launch and operate a warehoused ORS type of capability. There will not be a time when space-based ISR assets are not a viable way for us to divert and dilute some of an adversary's capabilities. Together, Operationally Responsive Space (ORS) and small satellites can ensure space-based ISR remains viable in support of Global Strike 2035 and remain an integral part of global ISR. In order to support Global Strike 2035 investment in ORS and small satellites are necessary if the ultimate goal is to enable the U.S. to meet future challenges head-on.

Finally, a balanced approach for Global ISR is a prerequisite for a fully informed Global Strike in 2035. The ISR portion of Global Strike will be the major component of Global Strike and thus necessitates the integration of as many ISR sources as can be explored. On their own, space, airborne, cyber, high altitude air platform, airship, and commercial ISR sources provide only one dimension for decision makers. By integrating these sources and providing decision makers with ubiquitous ISR, information will be transformed into actionable knowledge, thereby allowing U.S. decision makers to operate systematically within an adversary's Observe, Orient, Decide, Act (OODA) loop. These systems will provide vital contributions to Global Strike in 2035, which will in turn contribute greatly to U.S. national security.

VIII. Bibliography

AFCEA Intelligence Committee. *Space ISR in a Contested Environment*, October 2010.

Air Command and Staff College (ACSC) Space Research Electives Seminars. *AU-18 Space Primer, Chapter 13: US Space-Based Intelligence, Surveillance, and Reconnaissance,* September 2009, 167-179.

Air University Space Primer: *Chapter 22*, August 2003.

Bearden, David A. Small Satellite Costs, *Aerospace Crosslink*, http://www.aero.org/publications/crosslink/winter2001/04.html, Volume 2, Winter 2000/2001.

Ball, See Desmond. "Assessing China's ASAT Program," *Austral Special Report*, www.nautilus.org/~rmit/forum-reports/0714s-ball/, 14 June 2007.

Bell, William Scott. Air War College, Blue Horizons Paper, Center for Strategy and Technology: Blue Horizons. *Commercial Eyes in Space: Implications for U.S. Military Operations in 2030*, March 2008.

Bruce Carlson, Director of the National Reconnaissance, *NRO's Historical, Current, and Potential Future Use of Small Satellites*, 8 August 2011.

Carl Von Clausewitz, *On War*, trans. Peter Paret and Michael Howard, Princeton: Princeton University Press, 1976.

Chang, Chun-Chieh, Sharma,Yagya D., Kim, Yong-Sung. Bur, Jim A., Shenoi, Rajeev V., Krishna, Sanjay, Huang, Danhong, and Lin, Shawn-Yu. *A Surface Plasmon Enhanced Infrared Photodetector Based on In As Quantum Dots*. The Future Chips Constellation & Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, New York. Center for High Technology Materials, Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque, New Mexico. Space Vehicles Directorate, Air Force Research Laboratory, Kirtland Air Force Base, New Mexico.

Congressional Budget Office. *Recent Development Efforts for Military Airships*. November 2011.

Covault, Craig. Secret Inspection Satellites Boost Space Intelligence Ops, *Spaceflight Now*, 14 January 2009.

Creech, Gray. NASA Dryden Flight Research Center, *Boeing's Phantom Eye Aircraft Arrives at Dryden*. http://www.nasa.gov/centers/dryden/Features/phantom_eye_arrives.html, 28 March 2011.

Dahm, Dr.Werner J.A. *Technology Horizons: A Vision for Air Force Science and Technology during 2010-2030,Volume 1*. Washington, DC, Office of the US Air Force Chief Scientist, 15 May 2010.

Department of Defense. *Plan for Operationally Responsive Space A Report to Congressional Defense Committees*, 17 April 2007.

de Selding, Peter B. Shrinking Budgets Threaten NRO's Technology Demo Program, *Space News,* 17 October 2011.

Easton, Ian. Project 2049 Institute. *The Great Game in Space China's Evolving ASAT Weapons Programs and Their Implications for Future U.S. Strategy*, accessed 4 Dec 2011.

Final OSD Report on China's Military Power, Garreau, Joel, *Radical Evolution: The Promise and Peril of Enhancing our Minds, Our Bodies – and What It Means to Be Human*, (New York, NY: Doubleday) 2005.

Fisher, Richard. *China's Direct Ascent ASAT*, 20 January 2007; and Martin Sieff, "US Defense Intelligence Reports Chinese ASAT Weapon Utilized KT-1 Rocket," *Chinese Military Forum*, 26 January 2007.

Futron Corporation. *Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000*, http://www.futron.com, 6 September 2002.

Geis, John, Foster, Harry, Blanks, David, Kinnan, Chris, Hailes, Ted. *Blue Horizons (BH) II 2008 Final Report*. Center for Strategy and Technology (CSAT), Air University, Maxwell AFB, AL. 9 Aug 2011, 47.

Godefroy, A. B., & Canadian Forces Aerospace Warfare Centre. (2009). *Projecting Power: Canada's Air Force 2035*. Ottawa: Canadian Forces Aerospace Warfare Centre.

Guerra, Lisa. NASA, Exploration Systems Mission Directorate. *Space Systems Cost Estimating*, 2008.

Henry, Kenyon. *Air Force Wants to Trim Satellite Costs*, http://defensesystems.com, 10 November 2011.

Hertzfeld, Henry R., Williamson, Ray A., Peter, Nicolas. Space Policy Institute, *Launch Vehicles: An Economic Perspective*, September 2005.

Hsu, Jeremy, Bryner, Jeanna. *Space Arms Race Heats Up Overnight*, http://www.space.com/5007-space-arms-race-heats-overnight.html, 21 February 2008.

Janni, Joseph F., King, Yolanda Jones, Witt, Gerald. *An Innovative Approach to Satellite Technology.* Air Force Research Laboratory Air Force Office of Scientific Research, Arlington, VA., accessed 2 December 2011.

Kaku, Michio. *Physics of the Future - How Science Will Shape Human Destiny and Our Daily Lives by the Year 2100*. (New York): Doubleday, 2011.

Kaufman, Marc & Linzer, Dafna, *China Criticized for Anti-Satellite Missile Test*, Washington Post, 19 January 2007.

Kurzweil, Ray, *The Singularity Is Near: When Humans Transcend Biology*, (New York, NY: Penguin) 2005.

Lockheed Martin Aeronautics Company. *F-22 Raptor History*, http://www.f22-raptor.com/about/history.html, accessed 5 January 2012.

McGlaughlin, Kevin. Operationally *Responsive Space Office Briefing*, http://www.responsivespace.com, July 2007.

Milestone Reached for Operationally Responsive Space Satellite. http://www.spaceref.com/news/viewpr.rss.html?pid=34965, 14 October 2011.

National Security Space Strategy, *Unclassified Summary*, January 2011.

National Intelligence Council. 2025 *Global Trends Final Report*, November 2008.

Naval Research Laboratory, *Operationally Responsive Space (ORS) Launches*, http://www.nrl.navy.mil/media, accessed 4 December 2011.

Papadopoulos, Dennis. Physics Dept., University of MD. *Satellite Threat Due to High Altitude Nuclear Detonations*, accessed 4 December 2011.

Rao, Anil V., Scherich, Arthur E., Cox, Skylar, Mosher, Todd E. 6th Responsive Space Conference: *A Concept for Operationally Responsive Space Mission Planning Using Aeroassisted Orbital Transfer*, Los Angeles, CA., 28 April –1 May 2008.

Rendleman, James D., Faulconer, J. Walter Escaping the Space Acquisition Death Spiral, *High Frontier.*

Scharfl, Daniel P., Hadaegh, Fred Y., Kang, Bryan H. A *Survey of Formation Flying Guidance*. Jet Propulsion Laboratoy, California Institute of Technology, accessed 2 December 2011.

Singer, Jeremy. "Laser Links in Space," *Airforce-Magazine.com*, January 2008, http://www.airforcemagazine.com/Magazine/Archive/Pages/2008/January%202008/0108 laser.aspx, 26 May 2009.

Statement of Ambassador Gregory L. Schulte, Deputy Assistance Secretary of Defense for Space Policy before the Senate Committee on Armed Services Subcommittee on Strategic Forces, accessed 2 December 2011.

The Air Force Transformation Flight Plan, 2004.

The Boeing Company. *Boeing Unveils Unmanned Phantom Eye Demonstrator*, http://boeing.mediaroom.com/index.php?s=43&item=1306, 12 July 2010.

The Boeing Company. *Space Based Space Surveillance Mission Book*, Accessed 4 December 2011.

The Congressional Budget Office (CBO). *Recent Development Efforts for Military Airships*, November 2011.

Teets, Peter B. National Security Space in the Twenty-First Century, *Space Power Journal*, Summer 2004.

Tellis, Ashley J. China's Military Space Strategy, *Survival*, April 2007.

Types of Spacecraft Satellites & Space Probes, *The Encyclopedia of Science*. http://www.daviddarling.info/encyclopedia/S/spacecraft_list.html.

U.S. Air Force Fact Sheet, *Defense Support Program Satellites*, Air Force Space Command, Peterson AFB, http://www.af.mil/factsheets/factsheetasp?id=96, accessed 2 December 2011.

U.S. Air Force Fact Sheet, *Global Positioning System*, Air Force Space Command, Peterson AFB, http://www.af.mil/factsheets/factsheet.asp?ID=119, accessed 2 December 2011.

United States Air Force, *Strategic Planning, 2010-2030: Strategic Environmental Assessment*, Washington, DC, USAF Directorate of Strategic Planning, March 2011.

United States Air Force Chief Scientist (AF/ST) Report on Technology Horizons, *A Vision for Air Force Science & Technology During 2010-2030*, Vol. 1 AF/ST-TR-10-01-PR, 2010.

Viscito, Lauren, Richards, Matthew G., Ross, Adam M., *Assessing the Value Proposition for Operationally Responsive Space*, 1.

Visiongain Limited, *The Airborne ISR Market 2010-2020*, 2010.

Weeden, Brian. China's BX-1 microsatellite: a litmus test for space weaponization, *The Space Review*. http://www.thespacereview.com/article/1235/1, 20 Oct 2008.

West, Jessica, *Next Generation Space Security Challenges*, 18 December 2008.

Wingo, Dennis. *Toward a Theory of Spacepower, Chapter 8: Economic Development of the Solar System: The Heart of a 21st-century Spacepower Theory*, 166.

Zweck, Axel, Luther, Wolfgang. Applications of Nanotechnology in Space Developments and Systems Technological Analysis, *Future Technologies No. 47*, April 2003.

IX. Notes

[1] National Security Space Strategy, *Unclassified Summary*, January 2011, 4.
[2] *Blue Horizons (BH) II 2008 Final Report*, CSAT, Air University, Maxwell AFB, AL. 9 Aug 2011, 47.
[3] Ibid.
[4] Ibid.
[5] Bruce Carlson, Director of the National Reconnaissance. *NRO's Historical, Current, and Potential Future Use of Small Satellites*, 8 Aug 2011.
[6] *Statement of Ambassador Gregory L. Schulte*, Deputy Assistance Secretary of Defense for Space Policy before the Senate Committee on Armed Services Subcommittee on Strategic Forces, May 11, 2011.
[7] AFCEA Intelligence Committee. *Space ISR in a Contested Environment*, October 2010, 4.
[8] Congressional Budget Office. *Recent Development Efforts for Military Airships*. November 2011.
[9] *Categories of Satellite Earth Orbits*, Computational Physics, Inc., http://www.cpi.com/capabilities/ssa.html.
[10] Dennis Wingo. *Toward a Theory of Spacepower , Chapter 8: Economic Development of the Solar System: The Heart of a 21st-century Spacepower Theory*, 166.
[11] ACSC Space Research Electives Seminars. *AU-18 Space Primer*, *Chapter 13: US Space-Based ISR*, September 2009, 167-179.
[12] United States Air Force Chief Scientist. *Report on Technology Horizons, A Vision for Air Force Science & Technology During 2010-2030, Vol. 1*, 15 May 2010, 42.
[13] Jessica West, "Next Generation Space Security Challenges," *Security in Space: The Next Generation – Conference Report 31 March –1 April 2008*, (UNIDR), 2008, 40.
[14] Si-wen Wang, Li-hong Guo, and Ru-hai Guo, Changchun Institute of Optics, Fine Mechanics and Physics (China) and Graduate School of the Chinese Academy of Sciences (China), "*Analysis of LaserJjamming to Satellite-based Detector*, 2009.
[15] Ibid.
[16] Ibid.
[17] See Desmond Ball. "Assessing China's ASAT Program," *Austral Special Report*, www.nautilus.org/~rmit/forum-reports/0714s-ball/, 14 June 2007.
[18] Office of the Secretary of Defense, "Military Power of the People's Republic of China." *Department of Defense Annual Report to Congress*, 2003, 21.
[19] Marc Kaufman & Dafna Linzer, China Criticized for Anti-Satellite Missile Test, *Washington Post*, 19 Jan 2007.
[20] Richard Fisher. *China's Direct Ascent ASAT*, 20 January 2007; and Martin Sieff, "US Defense Intelligence Reports Chinese ASAT Weapon Utilized KT-1 Rocket," *Chinese Military Forum*, 26 January 2007.
[21] Jeremy Hsu and Jeanna Bryner. *Space Arms Race Heats Up Overnight*, http://www.space.com/5007-space-arms-race-heats-overnight.html, 21 February 2008.
[22] Brian Weeden. China's BX-1 microsatellite: A Litmus Test for Space Weaponization, *The Space Review*, http://www.thespacereview.com/article/1235/1, 20 Oct 2008.
[23] Craig Covault, Secret Inspection Satellites Boost Space Intelligence Ops, *Spaceflight Now*, 14 Jan 2009.
[24] *Air University Space Primer: Chapter 22*, Aug 2003.

[25] Dennis Papadopoulos. *Satellite Threat Due to High Altitude Nuclear Detonations*.
[26] Ibid.
[27] William Scott Bell. Blue Horizons Paper, CSAT: Blue Horizons. *Commercial Eyes in Space: Implications for U.S. Military Operations in 2030*, March 2008.
[28] The Boeing Company, *Boeing Unveils Unmanned Phantom Eye Demonstrator*, http://boeing.mediaroom.com/index.php?s=43&item=1306, 12 Jul 2010.
[29] Dave Deptula. *Intelligence, Surveillance and Reconnaissance, Air Force Unmanned Aerial System (UAS) Flight Plan 2009-2047*, 2009.
[30] Ibid.
[31] Department of Defense. *Plan for Operationally Responsive Space A Report to Congressional Defense Committees*, 17 April 2007, 3-4.
[32] Naval Research Laboratory. *ORS Launches*, http://www.nrl.navy.mil/media.
[33] "Endangered Birds," *The Economist* , 9 Dec 2010.
[34] Department of Defense. *Plan for Operationally Responsive Space A Report to Congressional Defense Committees*, 17 April 2007, 3-4.
[35] Lisa Guerra. NASA, Exploration Systems Mission Directorate, Space Systems Cost Estimating, 2008.
[36] The Encyclopedia of Science, Types of Spacecraft Satellites & Space Probes, http://www.daviddarling.info/encyclopedia/S/spacecraft_list.html.
[37] "Endangered Birds," *The Economist* , 9 Dec 2010.
[38] Ibid.
[39] Samuel L. Mcniel. USAF Proposed Tenets of Space Power: Six Enduring Truths, *Air and Space Power Journal*, Volume XVIII, No. 2, Summer 2004.
[40] "UCSB Physicists Demonstrate the Quantum von Neumann Architecture, a Quantum Processor, and a Quantum Memory on a Chip," http://www.nanotech-now.com/news.cgi?story_id=43311, 1 Sep 2011.
[41] Darren Quick. Gizmag, "New 'microlens' could lead to ultra-powerful satellite cameras and night-vision devices," http://www.gizmag.com/microlens-for-ultra-powerful-satellites-cameras-night-vision-devices/15153/, 20 May 2010.
[42] Ibid.
[43] Simone D'Amico and Oliver Montenbruck. Proximity Operations of Formation-Flying Spacecraft, Using an Eccentricity/Inclination Vector Separation, *Journal of Guidance, Control, and Dynamics*, Vol. 29, No. 3, May–June 2006.
[44] Raymond J. Sedwick, David W. Miller. *Electromagnetic Formation Flight, Final Report*, August 2005.
[45] AFCEA Intelligence Committee. *Space ISR in a Contested Environment*, October 2010, 1-5.
[46] Ian Easton. *The Great Game in Space China's Evolving ASAT Weapons Programs and Their Implications for Future U.S. Strategy*, 2-11.
[47] Lockheed Martin Aeronautics Company. F-22 Raptor History, http://www.f22-raptor.com/about/history.html, accessed 5 January 2012.
[48] Lauren Viscito, Matthew G. Richards, Adam M. Ross. *Assessing the Value Proposition for Operationally Responsive Space*, 1.
[49] Anil V. Rao, Arthur E. Scherich, Skylar Cox, Todd E. Mosher. 6th Responsive Space Conference: *A Concept for Operationally Responsive Space Mission Planning Using Aeroassisted Orbital Transfer*, Los Angeles, CA., 28 April –1 May 2008, 1.

[50] Department of Defense. *Plan for Operationally Responsive Space A Report to Congressional Defense Committees*, 17 April 2007, 12.
Anil V. Rao, Arthur E. Scherich, Skylar Cox, Todd E. Mosher. 6th Responsive Space Conference: *A Concept for Operationally Responsive Space Mission Planning Using Aeroassisted Orbital Transfer*, Los Angeles, CA., 28 April –1 May 2008.
[51] Ibid, 6-9.
[52] Kevin McGlaughlin. Operationally Responsive Space Office Briefing, http://www.responsivespace.com, July 2007, 9.
[53] William Scott Bell. Air War College, Blue Horizons Paper, Center for Strategy and Technology: Blue Horizons. *Commercial Eyes in Space: Implications for U.S. Military Operations in 2030*, March 2008, 17-19.
[54] Jeffrey Lewis. *Autonomous Proximity Operations: A Coming Collision in Orbit?*, 11 March 2004.
[55] Axel Zweck, Wolfgang Luther. Applications of Nanotechnology in Space Developments and Systems Technological Analysis, *Future Technologies No. 47*, April 2003.
[56] Anil V. Rao, Arthur E. Scherich, Skylar Cox, Todd E. Mosher. 6th Responsive Space Conference: *A Concept for Operationally Responsive Space Mission Planning Using Aeroassisted Orbital Transfer*, Los Angeles, CA., 28 April –1 May 2008, 2-4.
[57] Futron Corporation. *Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000*, http://www.futron.com, 6 September 2002, 1-6.
[58] Henry R. Hertzfeld, Ray A. Williamson, Nicolas Peter. Space Policy Institute, *Launch Vehicles: An Economic Perspective*, September 2005, 29-35.
[59] AFCEA Intelligence Committee. *Space ISR in a Contested Environment*, October 2010, 9.
[60] David A. Bearden. Small Satellite Costs, *Aerospace Crosslink*, http://www.aero.org/publications/crosslink/winter2001/04.html, Volume 2, Winter 2000/2001.